NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2376

METHOD FOR ANALYZING INDETERMINATE STRUCTURES STRESSED ABOVE PROPORTIONAL LIMIT

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University of Alabama

Washington

June 1951

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SUMMARY

An analytical method based on successive approximations is presented for determining the loads and deflections throughout an indeterminate structure in which one or more of the members have been stressed beyond their proportional limits.

Theoretical analyses of three structures are compared with tests and found to agree very closely. For the sake of simplicity and clarity, only coplanar pin-ended structures have been analyzed and tested.

INTRODUCTION

Various methods for determining loads in the members and displacements of joints of indeterminate structures are available. (See references 1 to 3.) However, all of these methods depend upon a linear relationship between stress and strain and since this linear relationship exists only when none of the stresses are above the proportional limit, they are not applicable if the stress in any part of the structure exceeds the proportional limit.

This paper presents a method of analyzing an indeterminate structure in which the stress in one or more members has exceeded the proportional limit. It is desirable to have such a method available since stresses in an indeterminate structure may accidentally or intentionally exceed the proportional limit. In such a case, it is important to be familiar with the behavior of the structures in this range. Also, it is possible that the margins of safety may be reduced after more is known about the behavior of an indeterminate structure in which some of the stresses have exceeded the proportional limit. (See reference 4.)

This work was conducted at the University of Alabama under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

A	cross-sectional area, square inches
L	length, inches
P	load in member, pounds
Q	total load, pounds
σ	normal stress, psi
E	Young's modulus of elasticity, psi
ϵ	normal strain, inch per inch
C	elastic coefficient (L/EA)
U	force in a bar caused by unit load acting in place of redundant bar, pounds
T	force in member caused by actual loading after all redundancies have been removed, pounds

THEORETICAL ANALYSIS

The basic concept of this method for analyzing indeterminate structures in which stresses exceed the proportional limit, is, except for a few minor changes, exactly the same as that of the relaxation method (reference 5). The procedure used can be explained best when applied to a special case. Consider the coplanar pin-connected truss shown in figure 1. The stress-strain curve for the material used in the truss is shown in figure 2.

The stresses in the four members and the deflection of point A corresponding to a load P may be determined by any standard indeterminate-structures method, provided that none of the stresses exceed the proportional limit of the material. However, suppose that the size of the members and the geometry of the truss is such that the load P causes the stress in member AB to exceed the proportional limit while the stresses in members AC, AD, and AE are below the proportional limit. If any of the standard methods were applied under this condition, the distribution of the loads obtained would be incorrect. This solution, as obtained by any of the standard methods, will be used as a first approximation of the true state of stress in the truss.

According to the results of such an analysis, the stress in member AB would, as shown in figure 2, equal OS and the strain would equal OU. This stress and this strain locate point Q in figure 2. Since the point Q does not lie on the stress-strain curve, it is impossible for the indicated stress and strain to exist in member AB. Also, the results of a standard method of analysis would show that point A has moved to some point, say A'. However, A' would be the new position of A only if OS and OU were the true stress and strain, respectively, in member AB. Since OS is not the true stress in member AB, an additional force acting at A in the direction AB is required to hold A in the position A'. This hypothetical force is equal to the difference between the actual load in member AB and its load as calculated by any standard method for analyzing indeterminate structures. When point A is in the position A', the actual stress and strain are given by point T in figure 2. The point T corresponds to stress OV, whereas the previous calculation gave a stress OS in member AB. Therefore, the hypothetical load required to hold point A at A' equals the product of the stress VS and the cross-sectional area of the member AB. It acts in the direction AB.

This hypothetical force, of course, is not actually applied to the truss; therefore, it must be liquidated in some way. This can be done by placing another force equal in magnitude but acting in opposite direction to the hypothetical force. The application of this force will induce additional loads in all four members and cause point A to move from the A' location to A", as shown in figure 1. Member AB is now subjected to a stress OL and a strain OM. This stress and this strain locate a point N. As before, it is concluded that since the point N does not lie on the stress-strain curve, OL and OM cannot represent the true stress and strain in member AB. However, since point N is closer to the stress-strain curve than Q, this second approximation is closer to the true condition than the first.

When point A is in the position A", the strain in member AB is equal to OM. Thus, with A in this new location A", the actual stress in member AB is equal to OK and the difference between the actual stress in member AB and the calculated stress is KL. The hypothetical force required to hold point A in the position A" is equal to the product of the stress KL and the cross-sectional area of member AB. Once more, as before, in order to liquidate this hypothetical force, another load, equal in magnitude but acting opposite in direction, is placed on the truss. This force is distributed among the members to obtain the third approximation. By repeating this process a sufficient number of times, the true stress and strain can be determined.

The rate at which the analysis converges depends on how close the applied load is to the ultimate load of the structure. If the applied load is well below the ultimate load, the analysis will converge rapidly. However, if the applied load is equal to or greater than the ultimate load, the analysis will diverge. If the analysis is divergent it will be apparent by the third approximation.

EXPERIMENTAL INVESTIGATION

Test Specimens

Three coplanar pin-ended trusses were tested. One truss was symmetrical with all members loaded in tension (figs. 3 and 4); one was unsymmetrical with all members loaded in tension (figs. 5 and 6); and one was unsymmetrical with one member loaded in compression (figs. 7 and 8). The lengths of the members shown in figures 3, 5, and 7 are their effective lengths rather than their true lengths. These effective lengths were determined by separate tests of the members including the clamps. All of the tension members were made of 1/8- by 1-inch 24S-T4 aluminum alloy and the compression member was made of 1/2- by 1-inch 24S-T4 aluminum alloy. The aluminum-alloy strips were clamped into steel end fittings, as shown in figure 9.

Test Apparatus

Load was applied to the trusses by means of a converted arbor press. A 1/4-horsepower motor, operating through a 4000 to 1 reduction gear box, raised or lowered the loading head at a uniform rate of 0.001 inch per second. The press was converted essentially to a straining machine. It could be stopped at any time with absolutely no reverse motion of the loading head. Figure 10 shows the attachment of the motor and gear box. Loads were measured by a 20,000-pound Dillon Dynamometer.

An adjustment was provided for keeping the pull always vertical. This was the 1- by 6-inch steel plate attached to the loading head. It appears in all photographs showing the trusses.

A Baldwin Southwark SR-4 type K strain indicator and type A-1 electric strain gages were used throughout the test.

Federal dial gages were used to measure the displacements.

Test Procedure

During the construction of the various test setups, every effort was made to insure conditions assumed in the computations; that is, each truss was as nearly coplanar and pin-ended as possible.

Because the members were so flexible, it was found impossible to get zero readings for the gages at a zero-load condition, even with the member removed from the setup entirely. To obtain zero readings various members were loaded in a statically determinate condition. Then, by recording the strain readings for each 500-pound increment of load up to 2500 pounds, the zero reading for each gage was obtained by interpolation. Zero readings for the gages on the vertical member were obtained in this way by disconnecting members other than the vertical.

The initial distribution of the load among the members of the truss was adjusted to equal the computed values by shifting one member. It was necessary to make such adjustments to remove the possibility of some of the members being initially stressed in the assembly of the truss. This adjustment was made by applying a load of 1000 pounds to the truss and adjusting the end fixtures until initial conditions were satisfied. After making these adjustments, the clamps were tightened and the test begun. No adjustments were made during the remainder of the test. The adjustments for the end fixtures are shown in figure 11.

Strain-gage and deflection readings were recorded for every 1000-pound increment of load. (See figs. 12 to 17.) In each case the load was increased until the stress in at least one of the members was well above the proportional limit.

Test Results and Discussion

Tension and compression stress-strain curves for the 24S-T4 material used are plotted in figures 18 and 19.

Figure 20 is a curve of average stress against average strain for the compression member of truss III. This figure was obtained from a compression test of a specimen identical to the compression member of truss III. The clamps used in truss III were also used for this compression test. Four SR-4 strain gages were located on the specimen in the same positions as on the compression member of truss III. The four strain-gage readings were averaged to give the average strain in the cross section where they were located. This average strain is plotted as the abscissa in figure 20. The average stress computed as the load divided by the cross-sectional area is plotted as the ordinate in figure 20. While not a true stress-strain curve, this type of curve is ideal for use in the analysis outlined in the appendix.

Tables I, II, and III compare the actual and computed loads in each member for the full loading range. For each truss it can be seen that the error is almost negligible.

The test with the truss with the compression member (figs. 7 and 8) proved to be an interesting experiment. In that test, the stress in the diagonal tension member exceeded the proportional limit first. After another 2500 pounds was added to the load, the stress in the vertical member exceeded the proportional limit. Then, after 1500 pounds more was added to the load, the compression member failed.

Unfortunately, the deflections plotted in figures 13, 15, and 17 cannot be checked analytically because no provision was made for measuring the deformation of the I-beam and the supporting frame during the performance of the tests. For this reason the theoretical displacements do not check with the actual displacements. However, since the theoretical and actual loads compared favorably, it is reasonable to assume the displacements would do likewise.

CONCLUSION

The method derived herein for the analysis of indeterminate structures, in which stresses exceed the proportional limit, gives results that agree well with experiments.

Although only coplanar pin-ended trusses were analyzed and tested, the method can be applied to more complex structures.

University of Alabama
University, Ala., May 30, 1950

APPENDIX

SAMPLE ANALYSIS

The analysis of truss II is carried out in detail. Later the analysis of truss III is presented also.

Truss II, for a Load Q

A diagrammatical sketch of truss II is shown in figure 5.

Until the stress in some member exceeds the proportional limit, the loads can be calculated by any indeterminate-structures method. Following is such an analysis using the elastic-energy method (reference 3) for redundant frames with member BO regarded as the redundant member.

Member	Length, L (in.)	Cross-sectional area, A (sq in.)	$C = \frac{L}{AE}$	U	T	CUT	CU^2
AO	25.5	0.125	0.0000194	-1.905	Q	-0.0000369Q	0.0000705
BO	50.0	.125	.0000380	1.000	0	0	.0000380
CO	27.0	.125	.0000205	1.250	0	0	.0000321

$$\Sigma CUT = -0.0000369Q$$

$$\Sigma CU^2 = 0.0001406$$

$$P_B = -\frac{\Sigma CUT}{\Sigma CU^2} = \frac{0.0000369Q}{0.0001406} = 0.263Q$$

$$P_A = Q - 0.263Q(1.905) = 0.502Q$$

$$P_C = 0.263Q(1.250) = 0.328Q$$

With 14,000 pounds on the truss and if a linear stress-strain relationship holds, the stresses in the truss subjected to 14,000 pounds will be:

$$\sigma_A = \frac{0.502 \times 14,000}{0.125} = 56,224 \text{ psi}$$

$$\sigma_B = \frac{0.263 \times 14,000}{0.125} = 29,456 \text{ psi}$$

$$\sigma_C = \frac{0.328 \times 14,000}{0.125} = 36,736 \text{ psi}$$

and the corresponding strains will be:

$$\epsilon_A = \frac{56,224}{10.52 \times 10^6} = 5344 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_B = \frac{29,456}{10.52 \times 10^6} = 2800 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_C = \frac{36,736}{10.52 \times 10^6} = 3492 \times 10^{-6} \text{ inch per inch}$$

As a result of these strains, point O will move to a new position, and, vice versa, if point O is moved to this new position, the foregoing strains will result. However, the stress-strain curve shows that, corresponding to these strains, the stresses will be (from fig. 18):

$$\sigma_A = 49,400 \text{ psi} \quad \sigma_B = 29,456 \text{ psi} \quad \sigma_C = 36,736 \text{ psi}$$

Thus, if point O is placed in this new position, an external force is required to hold it there since member OA is not carrying its share of the load. Member OA should carry $56,224 \times 0.125 = 7028$ pounds; OA actually carries $49,400 \times 0.125 = 6175$ pounds. Therefore, $7028 - 6175 = 853$ pounds is required to supplement the load carried by member OA.

A summary of conditions at this time is: Point O is in the position it would assume if a linear stress-strain relationship held in all members,

$$\sigma_A = 49,400 \text{ psi} \qquad \epsilon_A = 5344 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_B = 29,456 \text{ psi} \qquad \epsilon_B = 2800 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_C = 36,736 \text{ psi} \qquad \epsilon_C = 3492 \times 10^{-6} \text{ inch per inch}$$

and 853 pounds is acting at point O in the direction OA.

Since the 853 pounds is a hypothetical load, it must be liquidated in some way. This is accomplished by placing another 853-pound load on the structure at point O which acts so as to cancel the 853-pound hypothetical load.

Because of the action of the added 853-pound load, point O will move to a new position. A position, consistent with the strains in the members, can be found if it is assumed that all members act in a linear stress-strain relationship.

Under this assumption, the additional stresses imposed in the members by the 853 pounds are:

$$\sigma_A = \frac{0.502 \times 853}{0.125} = 3425 \text{ psi}$$

$$\sigma_B = \frac{0.263 \times 853}{0.125} = 1795 \text{ psi}$$

$$\sigma_C = \frac{0.328 \times 853}{0.125} = 2238 \text{ psi}$$

and the additional strains in the members are:

$$\epsilon_A = \frac{3425}{10.52 \times 10^6} = 326 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_B = \frac{1795}{10.52 \times 10^6} = 171 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_C = \frac{2238}{10.52 \times 10^6} = 213 \times 10^{-6} \text{ inch per inch}$$

Thus, the apparent total stresses in the members are:

$$\sigma_A = 49{,}400 + 3425 = 52{,}825 \text{ psi}$$

$$\sigma_B = 29{,}456 + 1795 = 31{,}251 \text{ psi}$$

$$\sigma_C = 36{,}736 + 2238 = 38{,}974 \text{ psi}$$

However, the stress-strain curve shows that the stresses in members corresponding to strains consistent with the position of point O are:

$$\sigma_A = 49{,}800 \text{ psi} \quad \sigma_B = 31{,}251 \text{ psi} \quad \sigma_C = 38{,}974 \text{ psi}$$

Thus, if point O is to maintain this new position, an external force is required to supplement the load carried by OA. Member OA should carry $52{,}825 \times 0.125 = 6603$ pounds; OA actually carried $49{,}800 \times 0.125 = 6225$ pounds.

Therefore, $6603 - 6225 = 378$ pounds is required to supplement the load carried by member OA.

Now applying 378 pounds at point O to cancel this hypothetical force induces, under a linear stress-strain assumption, the following stresses in the members:

$$\sigma_A = \frac{0.502 \times 378}{0.125} = 1518 \text{ psi}$$

$$\sigma_B = \frac{0.263 \times 378}{0.125} = 795 \text{ psi}$$

$$\sigma_C = \frac{0.328 \times 378}{0.125} = 992 \text{ psi}$$

Thus the total apparent stresses in the members are

$$\sigma_A = 49,800 + 1518 = 51,318 \text{ psi}$$

$$\sigma_B = 31,251 + 795 = 32,046 \text{ psi}$$

$$\sigma_C = 38,974 + 992 = 39,966 \text{ psi}$$

However, once again, from the stress-strain curve for strains consistent with the position of the point O, the stresses are:

$$\sigma_A = 49,900 \text{ psi} \quad \sigma_B = 32,046 \text{ psi} \quad \sigma_C = 39,966 \text{ psi}$$

The load in member OA must be supplemented by the amount $(51,318 - 49,900)(0.125) = 177$ pounds.

In order to eliminate this hypothetical load, a 177-pound load is placed on the structure. It induces the additional stresses:

$$\sigma_A = 711 \text{ psi} \quad \sigma_B = 372 \text{ psi} \quad \sigma_C = 464 \text{ psi}$$

The apparent total stresses are:

$$\sigma_A = 50{,}611 \text{ psi} \quad \sigma_B = 32{,}418 \text{ psi} \quad \sigma_C = 40{,}430 \text{ psi}$$

However, the stresses consistent with the strains in the members are:

$$\sigma_A = 49{,}950 \text{ psi} \quad \sigma_B = 32{,}418 \text{ psi} \quad \sigma_C = 40{,}430 \text{ psi}$$

Therefore, member OA must be supplemented by an amount $(50{,}611 - 49{,}950)(0.125) = 83$ pounds. This is considered negligible.

The loads carried by the members are:

$$P_A = 49{,}950 \times 0.125 = 6243 \text{ pounds}$$

$$P_B = 32{,}418 \times 0.125 = 4052 \text{ pounds}$$

$$P_C = 40{,}430 \times 0.125 = 5054 \text{ pounds}$$

The test gave (see table II):

$$P_A = 6245 \text{ pounds}$$

$$P_B = 4085 \text{ pounds}$$

$$P_C = 5070 \text{ pounds}$$

Overbalancing Method

In the foregoing analysis the total load

$$14{,}000 + 853 + 378 + 177 = 15{,}408 \text{ pounds}$$

has been applied to the truss. Based on a linear stress-strain relation, the stresses in the members are:

$$\sigma_A = \frac{0.502 \times 15{,}408}{0.125} = 61{,}879 \text{ psi}$$

$$\sigma_B = \frac{0.263 \times 15{,}408}{0.125} = 32{,}418 \text{ psi}$$

$$\sigma_C = \frac{0.328 \times 15{,}408}{0.125} = 40{,}131 \text{ psi}$$

and the corresponding strains will be:

$$\epsilon_A = \frac{61{,}879}{10.52 \times 10^6} = 5882 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_B = \frac{32{,}418}{10.52 \times 10^6} = 3082 \times 10^{-6} \text{ inch per inch}$$

$$\epsilon_C = \frac{40{,}431}{10.52 \times 10^6} = 3843 \times 10^{-6} \text{ inch per inch}$$

Under a linear stress-strain relationship, the displacement of point O due to the 15,408 pounds is easily determined. Its position will be consistent with the strains computed for each member. However, the stress-strain curve shows that the stresses corresponding to the strains consistent with the position of O are:

$$\sigma_A = 49{,}950 \text{ psi} \quad \sigma_B = 32{,}400 \text{ psi} \quad \sigma_C = 40{,}500 \text{ psi}$$

By comparing these values with those obtained by the longer method, it can be seen that the only difference lies in one's ability to read the stress-strain curve closer.

Truss III, for $Q = 14{,}000$ Pounds

Under a 14,000-pound load the stresses in the members of truss III have all exceeded the elastic limit. The truss at 14,000 pounds is loaded almost to its ultimate, and to insure rapid convergence the overbalancing method should be used.

The members in the truss must be so loaded that they will support a 14,000-pound vertical load. First, overbalance by placing a 20,000-pound vertical load on the truss. Under a linear stress-strain relationship, the stresses and strains in the members will be

$$\sigma_A = 47{,}000 \text{ psi} \qquad \epsilon_A = 4490 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_B = 92{,}960 \text{ psi} \qquad \epsilon_B = 8840 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_C = -18{,}780 \text{ psi} \qquad \epsilon_C = -9630 \times 10^{-6} \text{ inch per inch}$$

However, the stresses consistent with the strains as obtained from figures 18 and 20 are

$$\sigma_A = 46{,}300 \text{ psi} \quad \sigma_B = 51{,}500 \text{ psi} \quad \sigma_C = 10{,}910 \text{ psi}$$

A check of the vertical and horizontal components shows that under the stresses actually existing in the members, the truss will be carrying a vertical load of 13,741 pounds and a horizontal load of 200 pounds.

Now overbalance by placing a 21,500-pound vertical load and a 4000-pound negative horizontal load on the truss. Under a linear stress-strain relationship, the stresses and the strains in the members are

$$\sigma_A = 49{,}972 \text{ psi} \qquad \epsilon_A = 4750 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_B = 119{,}100 \text{ psi} \qquad \epsilon_B = 11{,}320 \times 10^{-6} \text{ inch per inch}$$

$$\sigma_C = -14{,}289 \text{ psi} \qquad \epsilon_C = -7330 \times 10^{-6} \text{ inch per inch}$$

The actual stresses corresponding to the strains are

$$\sigma_A = 47{,}900 \text{ psi} \quad \sigma_B = 52{,}800 \text{ psi} \quad \sigma_C = -10{,}620 \text{ psi}$$

The loads in the members are

$$P_A = 5988 \text{ pounds} \quad P_B = 6600 \text{ pounds} \quad P_C = -5310 \text{ pounds}$$

A check of the vertical and horizontal components shows that the truss is carrying a 13,980-pound vertical load and a 27-pound horizontal load. The error is considered negligible.

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TABLE I.- ACTUAL AND COMPUTED LOADS IN MEMBERS OF TRUSS I

	Member AO			Member BO			Member CO		
Applied load (lb)	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference
1000	495	496	0.20	330	328	-0.60	305	310	1.63
2000	995	992	-0.30	665	656	0.15	610	620	1.63
3000	1490	1488	-0.13	985	984	-0.10	920	930	1.08
4000	1990	1984	-0.30	1310	1312	0.15	1230	1240	0.81
5000	2495	2480	-0.60	1635	1640	0.31	1545	1550	0.32
6000	2980	2976	-0.13	1965	1968	0.15	1850	1880	1.62
7000	3485	3472	-0.37	2295	2296	0.04	2165	2170	0.23
8000	3980	3968	-0.55	2625	2624	-0.04	2470	2480	0.40
9000	4470	4464	-0.13	2950	2952	0.07	2785	2790	0.18
10,000	4965	4960	-0.10	3275	3280	0.15	3090	3100	0.32
11,000	5460	5456	-0.07	3600	3608	0.22	3405	3410	0.15
12,000	5880	5875	-0.09	3970	3985	0.38	3765	3766	0.03
13,000	6105	6075	-0.49	4450	4526	1.71	4225	4278	1.25
14,000	6230	6163	-1.08	5030	5116	1.71	4790	4836	0.96
15,000	6275	6288	0.21	5670	5638	-0.56	5415	5363	-0.96

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TABLE II.- ACTUAL AND COMPUTED LOADS IN MEMBERS OF TRUSS II

	Member AO			Member BO			Member CO		
Applied load (lb)	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference
1000	499	502	0.60	273	263	-3.66	322	328	1.86
2000	1006	1004	-0.20	522	526	0.77	653	656	0.46
3000	1502	1506	0.27	787	789	0.25	985	984	-0.10
4000	2002	2008	0.30	1051	1052	0.10	1313	1312	-0.08
5000	2510	2510	0	1313	1315	0.15	1645	1640	-0.30
6000	3010	3012	0.07	1575	1578	0.19	1976	1968	-0.40
7000	3510	3514	0.11	1842	1841	-0.05	2303	2296	-0.30
8000	4010	4016	0.15	2114	2104	-0.47	2642	2624	-0.68
9000	4510	4518	0.18	2375	2367	-0.34	2981	2952	-0.97
10,000	5000	5020	0.40	2640	2630	-0.38	3325	3280	-1.35
11,000	5450	5481	0.55	2905	2906	0.03	3670	3624	-0.13
12,000	5825	5909	1.44	3185	3205	0.63	4050	3997	-1.31
13,000	6110	6150	0.65	3535	3599	0.46	4480	4489	0.20
14,000	6245	6243	-0.03	4085	4052	-0.91	5070	5054	-0.32

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TABLE III.- ACTUAL AND COMPUTED LOADS IN MEMBERS OF TRUSS III

	Member AO			Member BO			Member CO		
Applied load (lb)	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference	Actual load (lb)	Theoretical load (lb)	Percent difference
1000	300	295	-1.66	580	581	0.17	460	469	1.96
2000	590	590	0	1170	1162	-0.68	930	938	0.86
3000	900	885	-1.67	1750	1743	-0.40	1395	1407	0.86
4000	1195	1180	-1.26	2340	2324	-0.68	1860	1876	0.86
5000	1490	1475	-1.01	2925	2905	-0.68	2325	2345	0.86
6000	1800	1770	-1.67	3510	3486	-0.68	2800	2814	0.50
7000	2090	2065	-1.19	4100	4067	-0.80	3270	3283	0.40
8000	2390	2360	-1.26	4675	4648	-0.58	3730	3752	0.80
9000	2690	2655	-1.30	5220	5229	0.17	4200	4221	0.50
10,000	3030	3018	-0.40	5710	5781	1.24	4670	4675	0.11
11,000	3510	3444	-1.88	6120	6188	1.11	5080	5020	-1.18
12,000	4210	4300	2.14	6350	6334	-0.94	5290	5150	-2.64
13,000	5030	5187	3.12	6490	6463	-0.42	5390	5175	-3.98
14,000	5950	5988	0.64	6575	6600	0.38	5450	5310	-2.64

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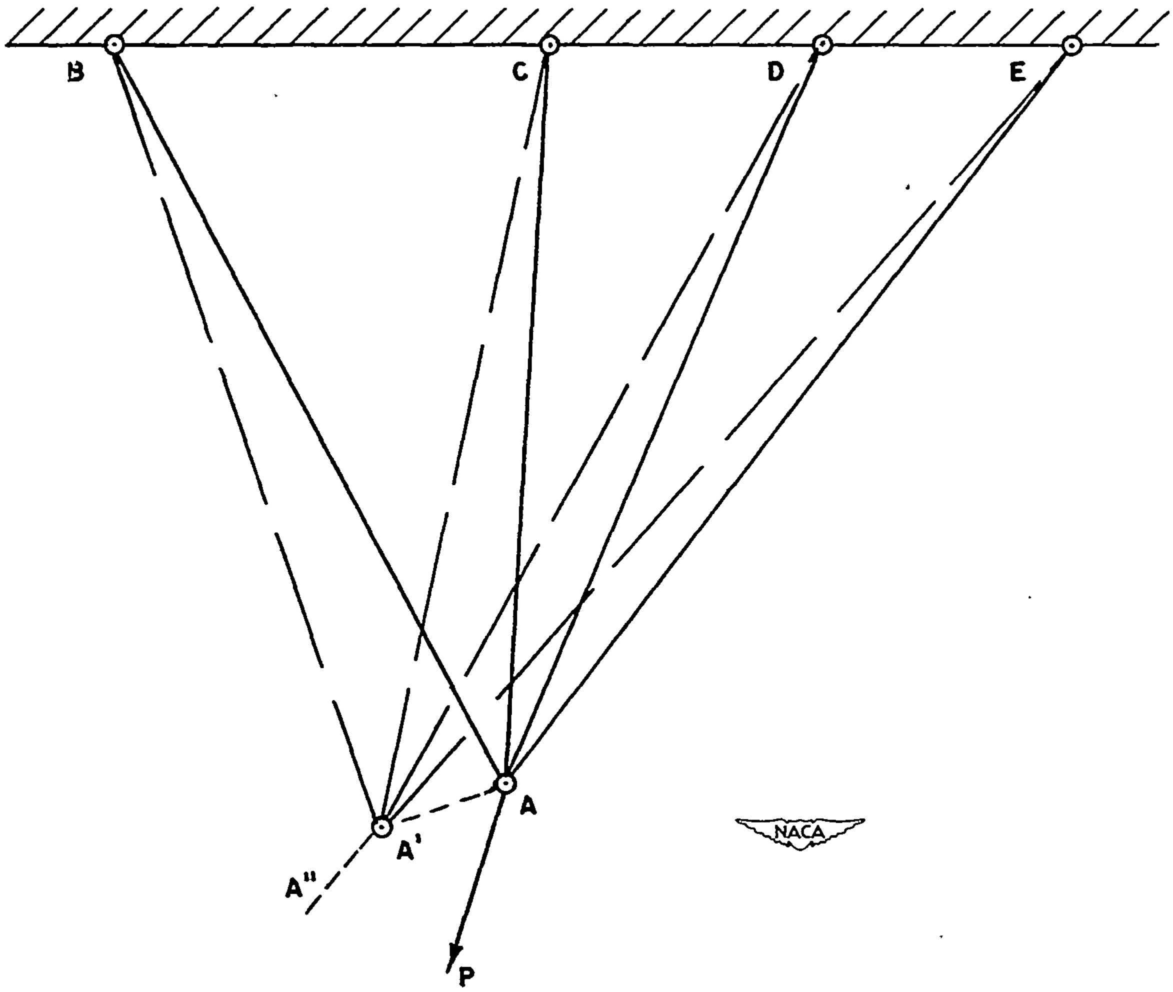

Figure 1.- Coplanar pin-connected truss.

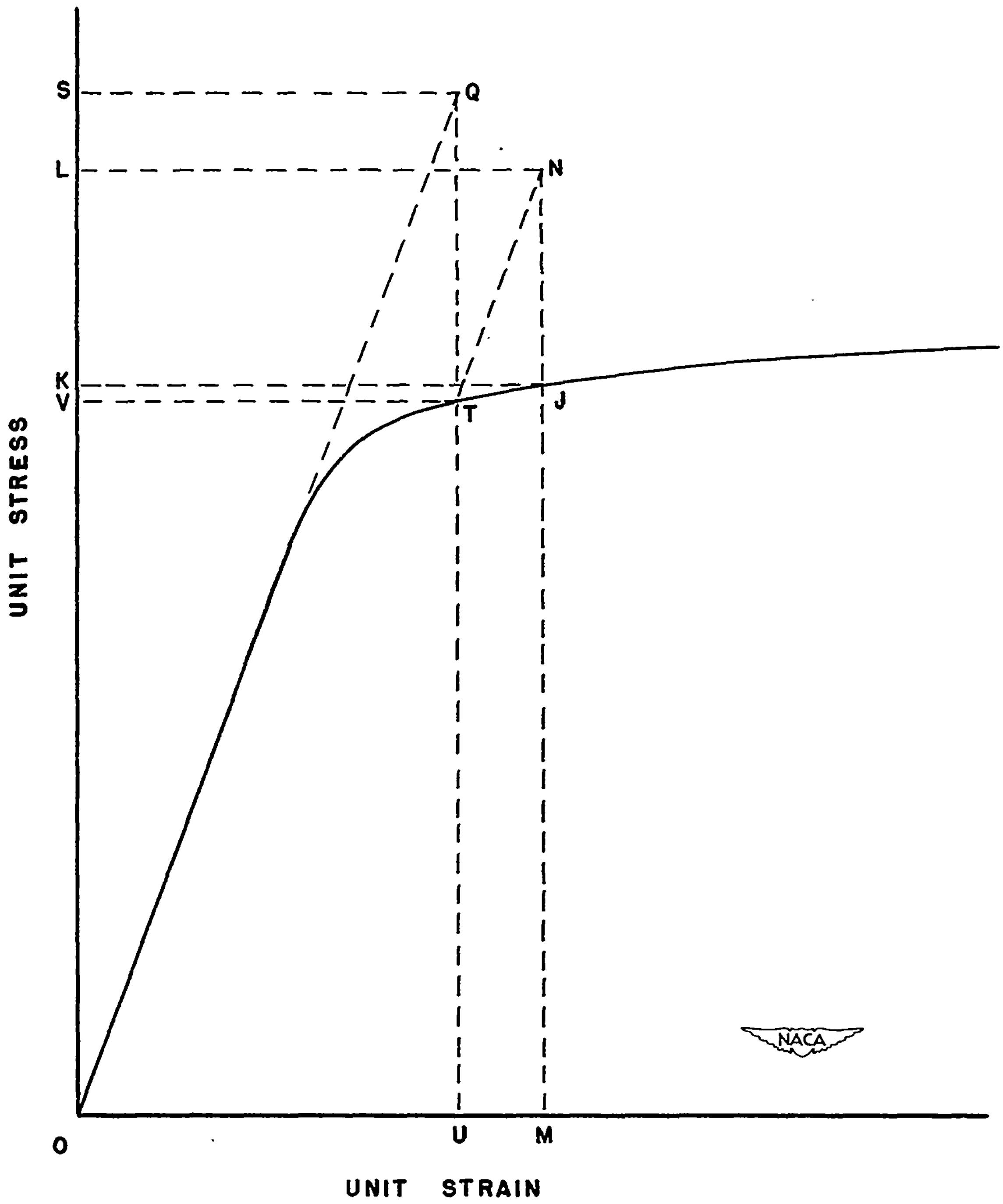

Figure 2.- Stress-strain curve of material used in truss of figure 1. Curve is typical stress-strain curve for aluminum alloy.

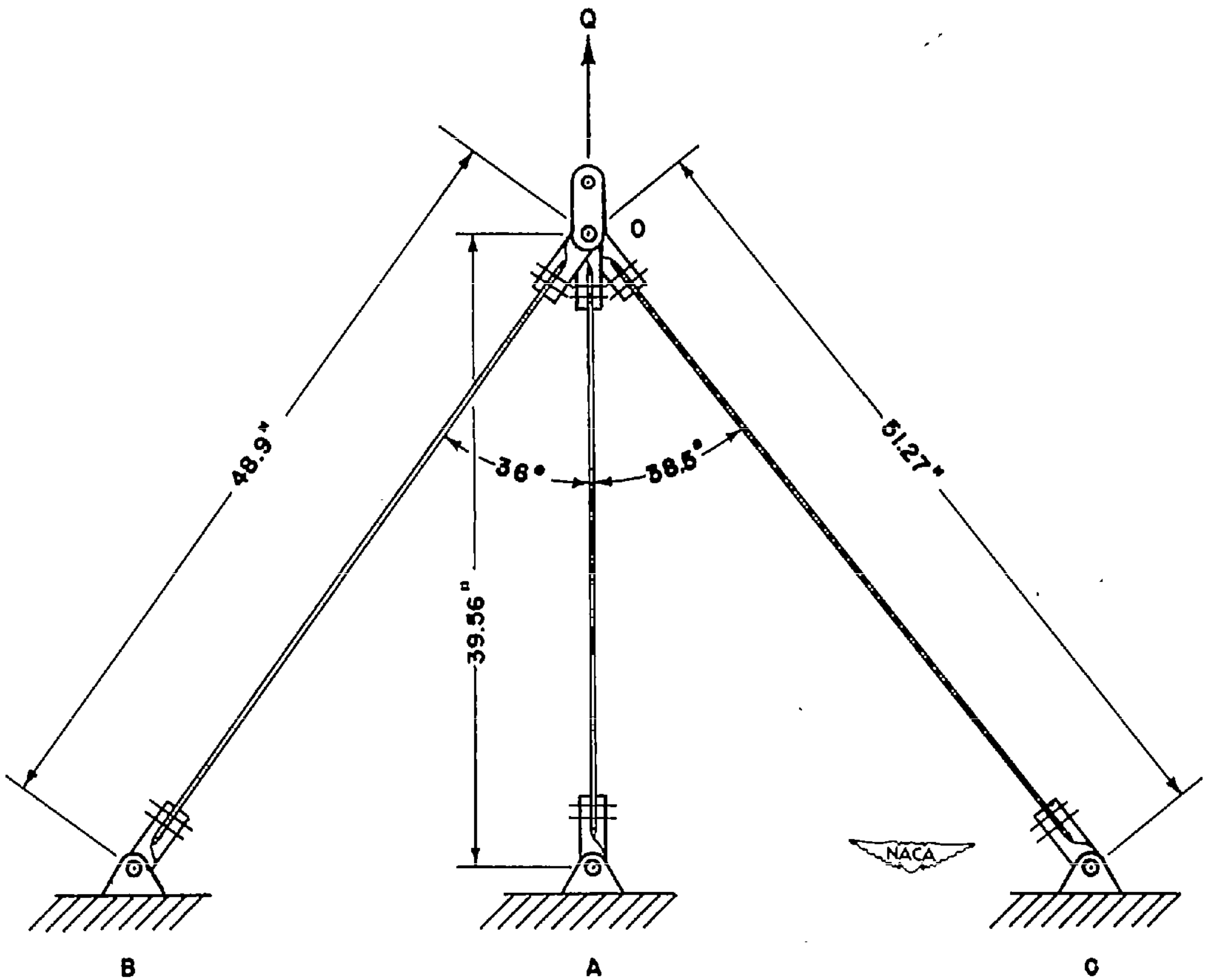

Figure 3.- Truss I. All members are 24S-T4 aluminum alloy, 1 by 1/8 inch.

Figure 4.- Symmetrical, coplanar, pin-ended truss I.

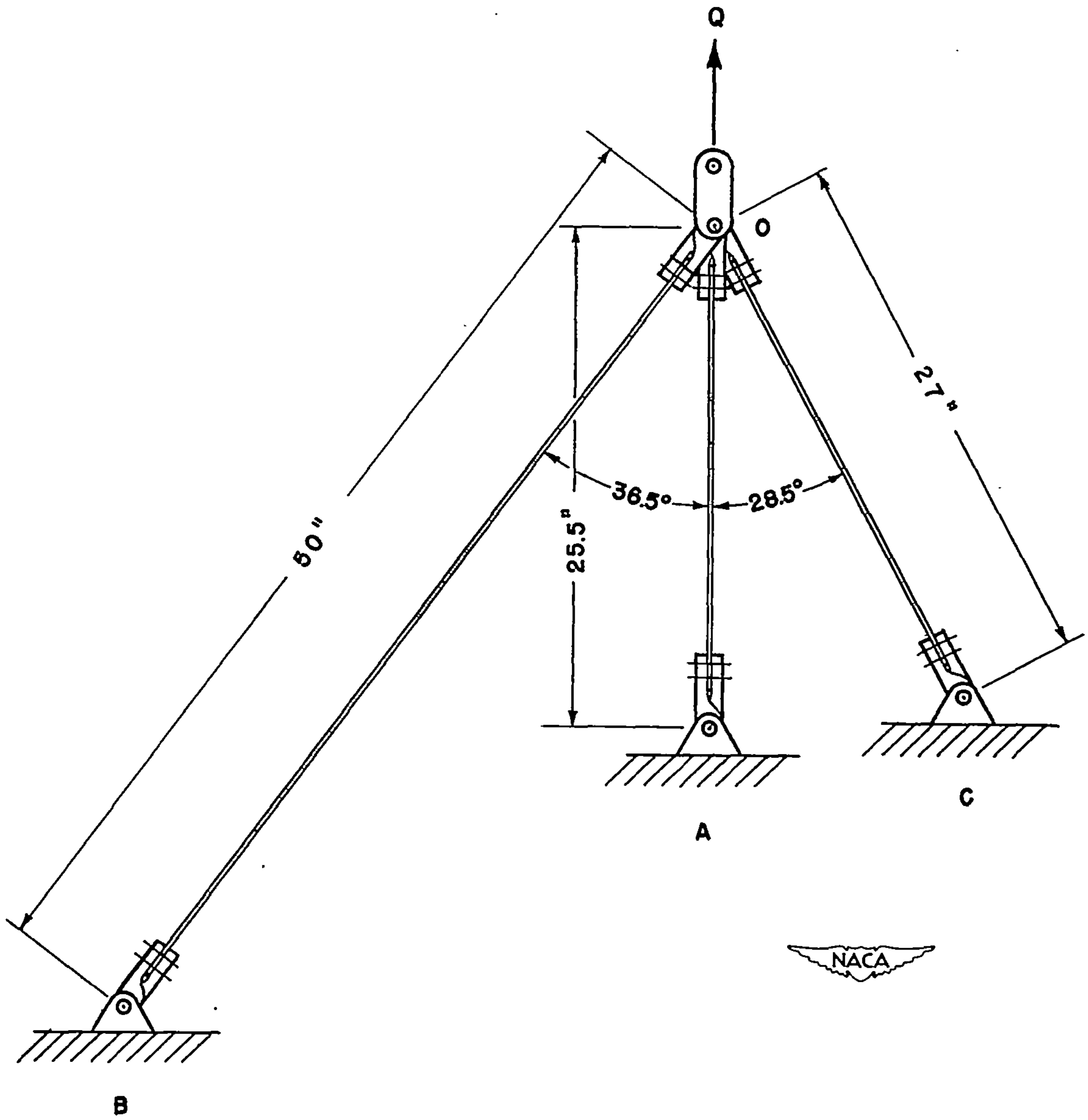

Figure 5.- Truss II. All members are 24S-T4 aluminum alloy, 1 by 1/8 inch.

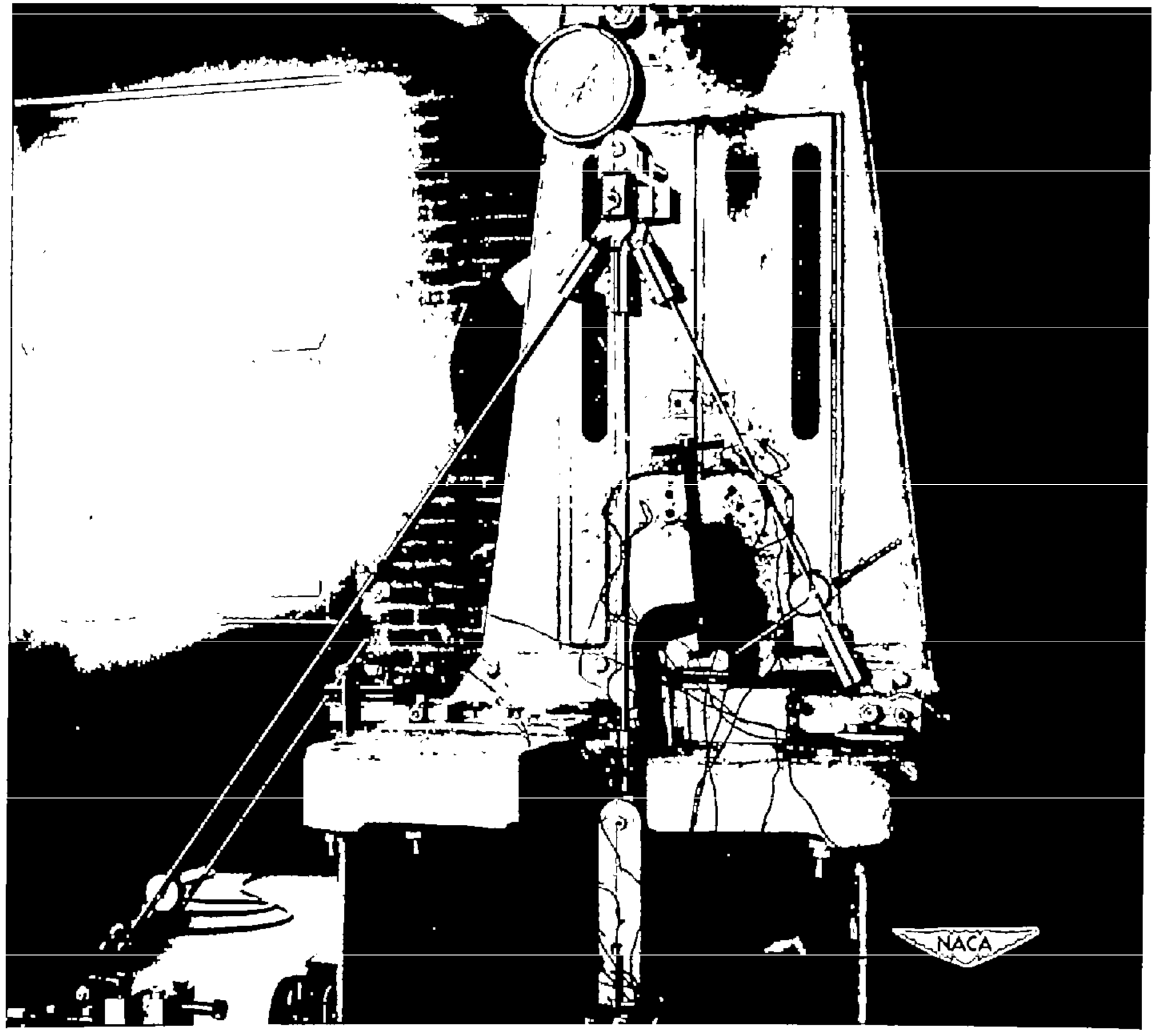

Figure 6.- Unsymmetrical, coplanar, pin-ended truss II. All members in tension.

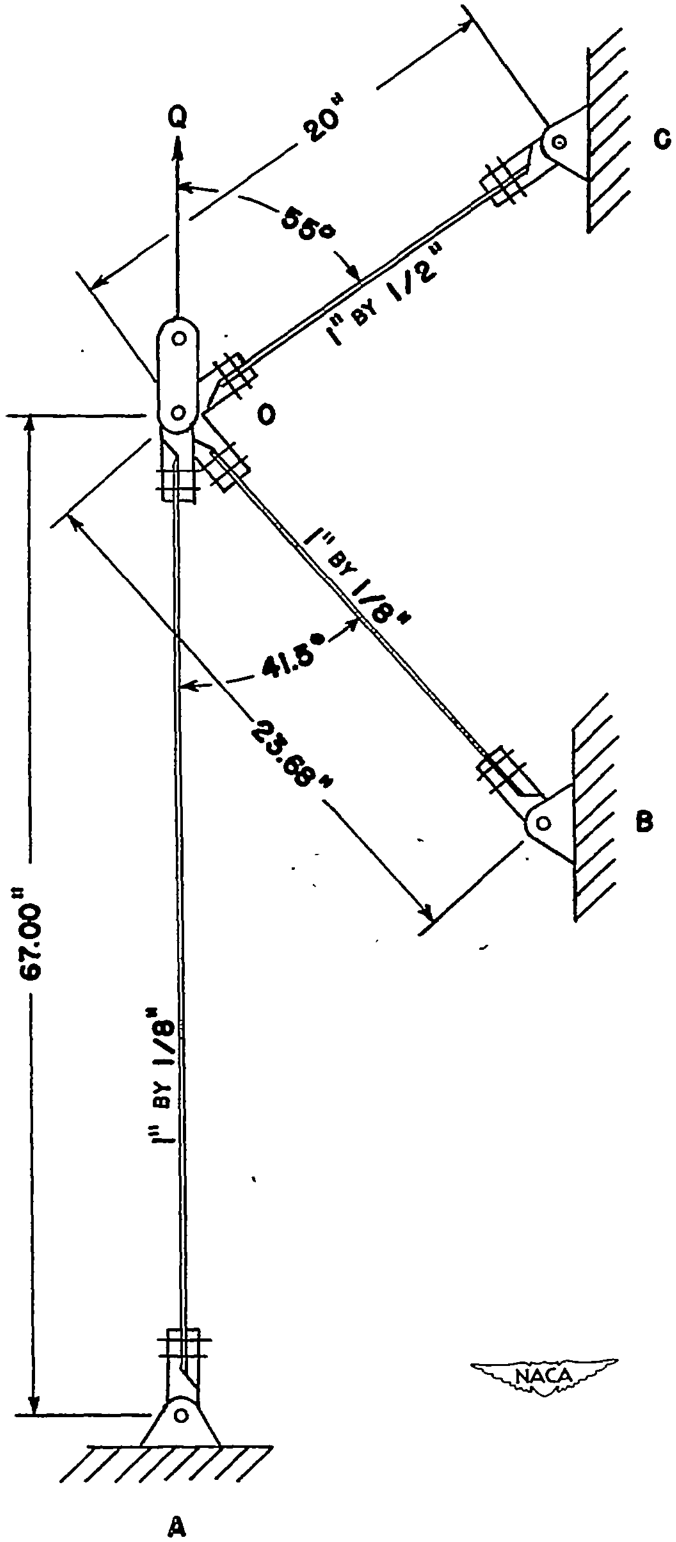

Figure 7.- Truss III. All members are 24S-T4 aluminum alloy.

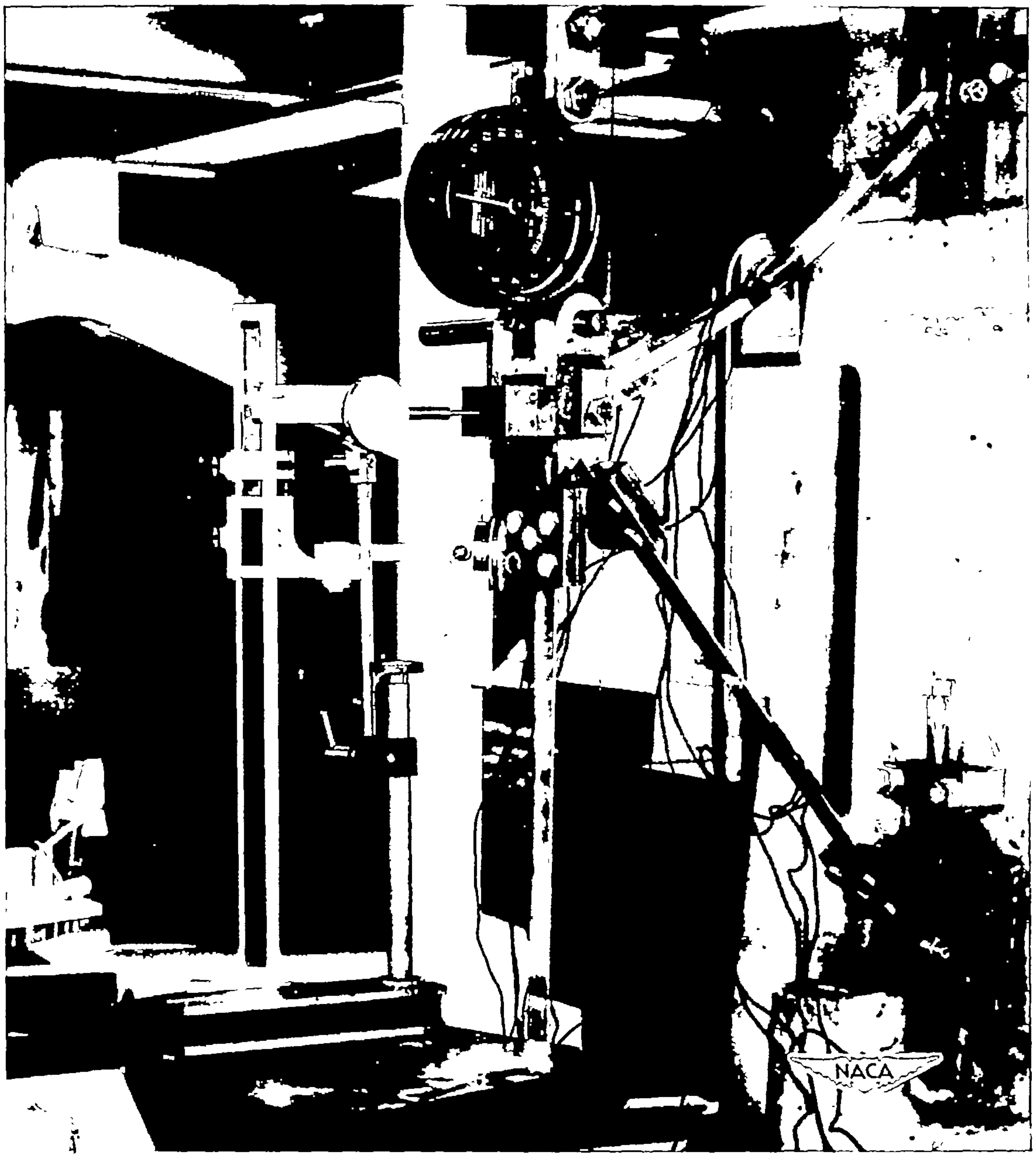

Figure 8.- Unsymmetrical, coplanar, pin-ended truss III. One member in compression.

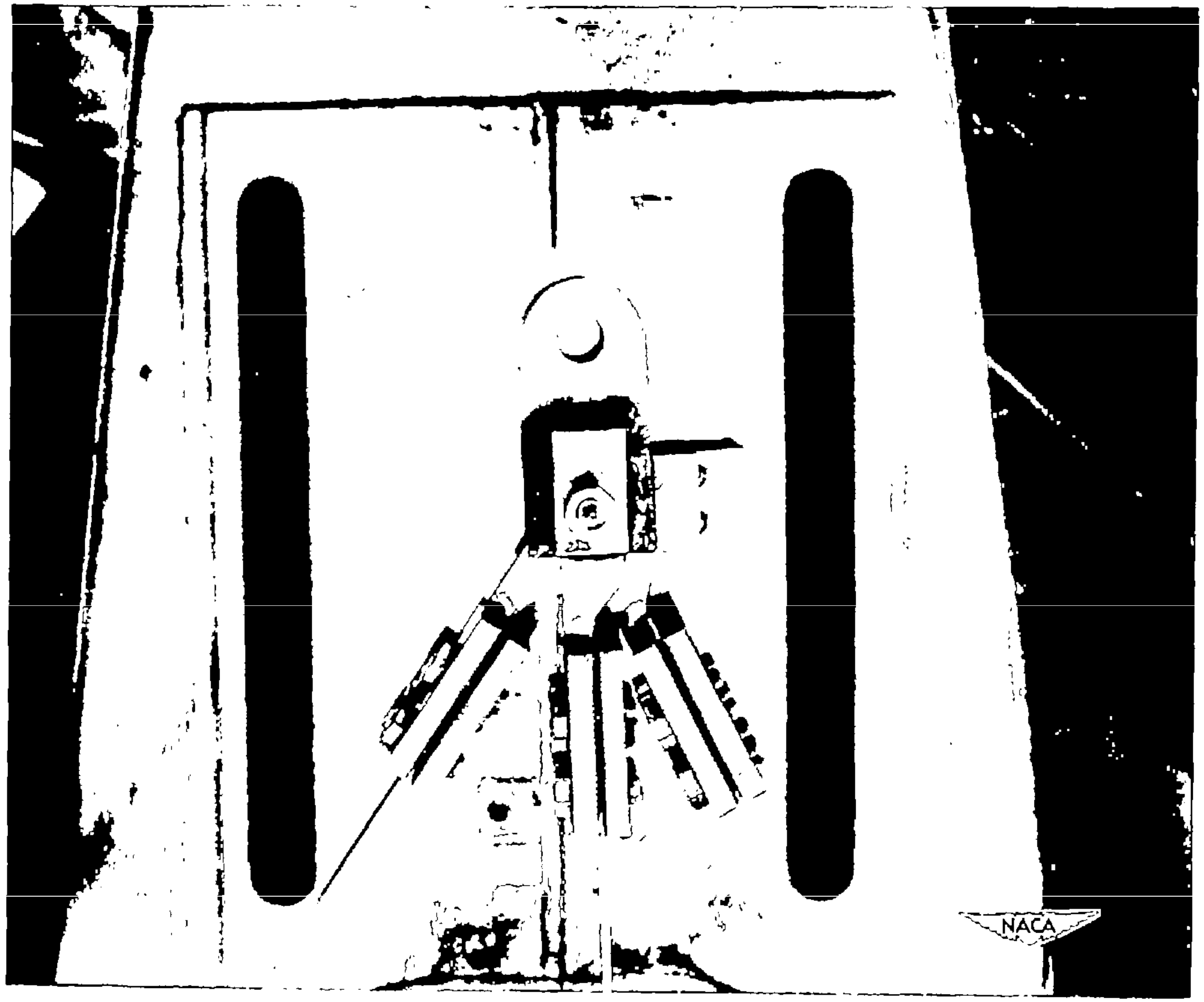

Figure 9.- Steel clamps and clevis.

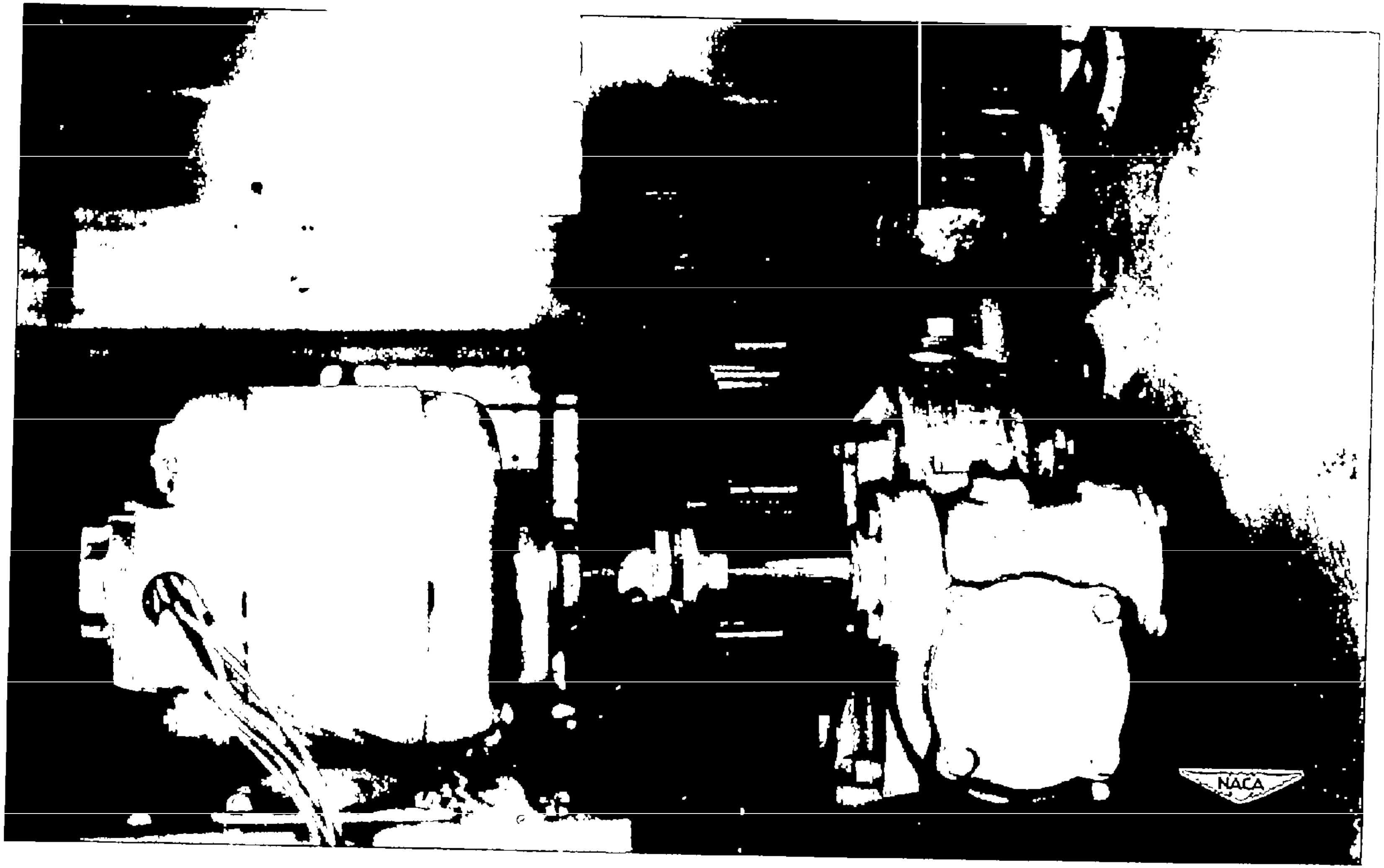

Figure 10.- Motor and gear box.

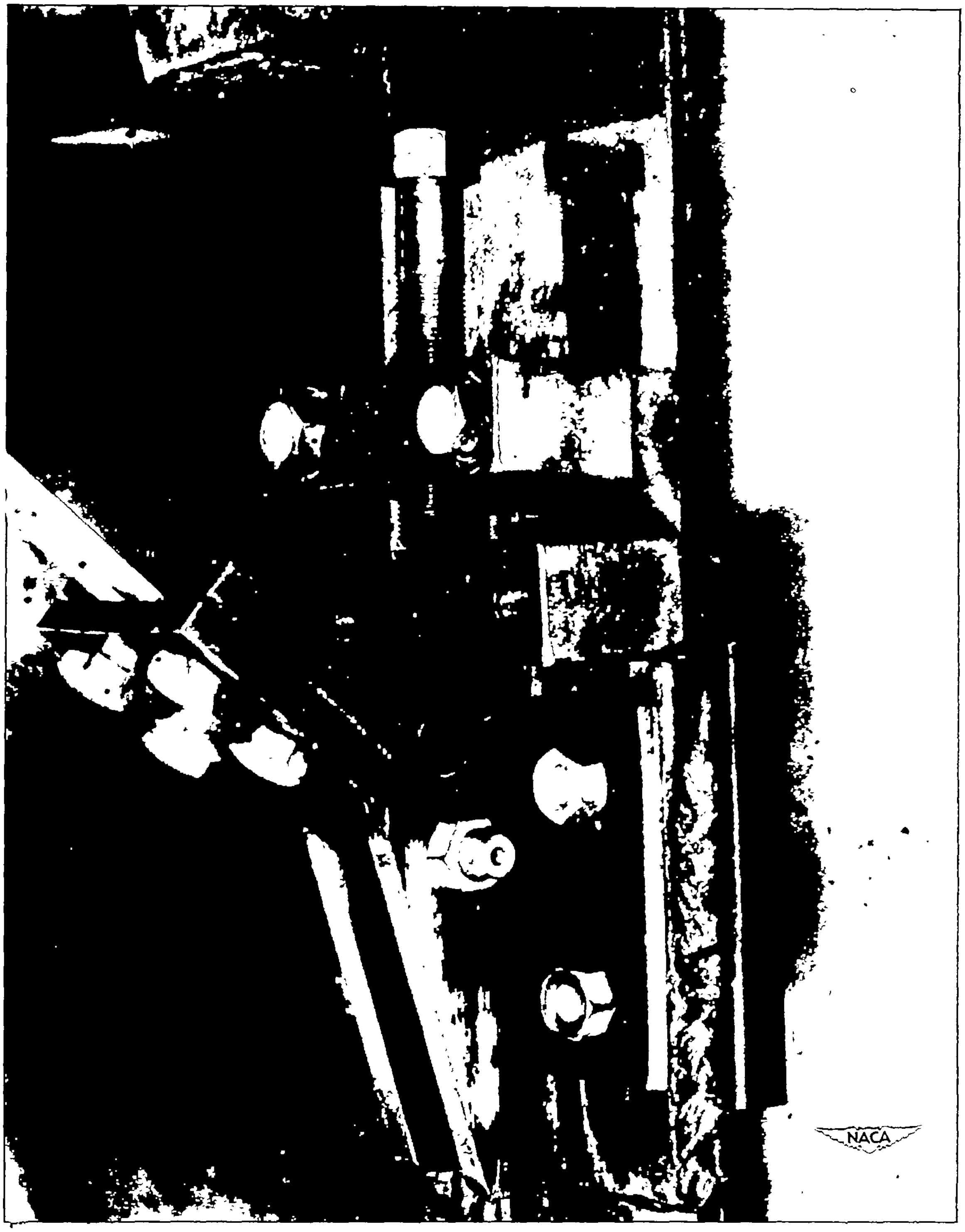

Figure 11.- Steel clamp and adjustments.

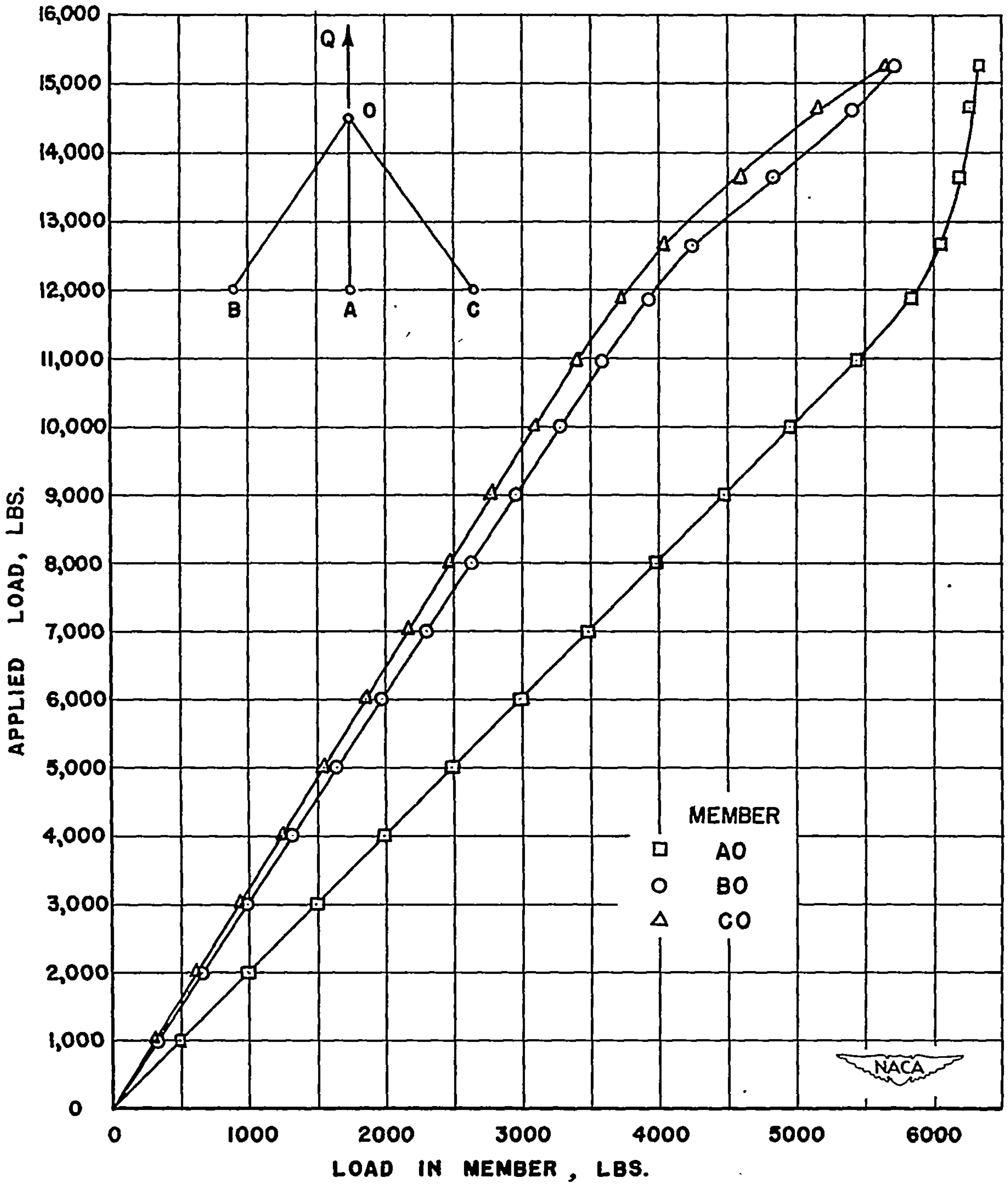

Figure 12.- Curves of applied load against load in members for truss I.

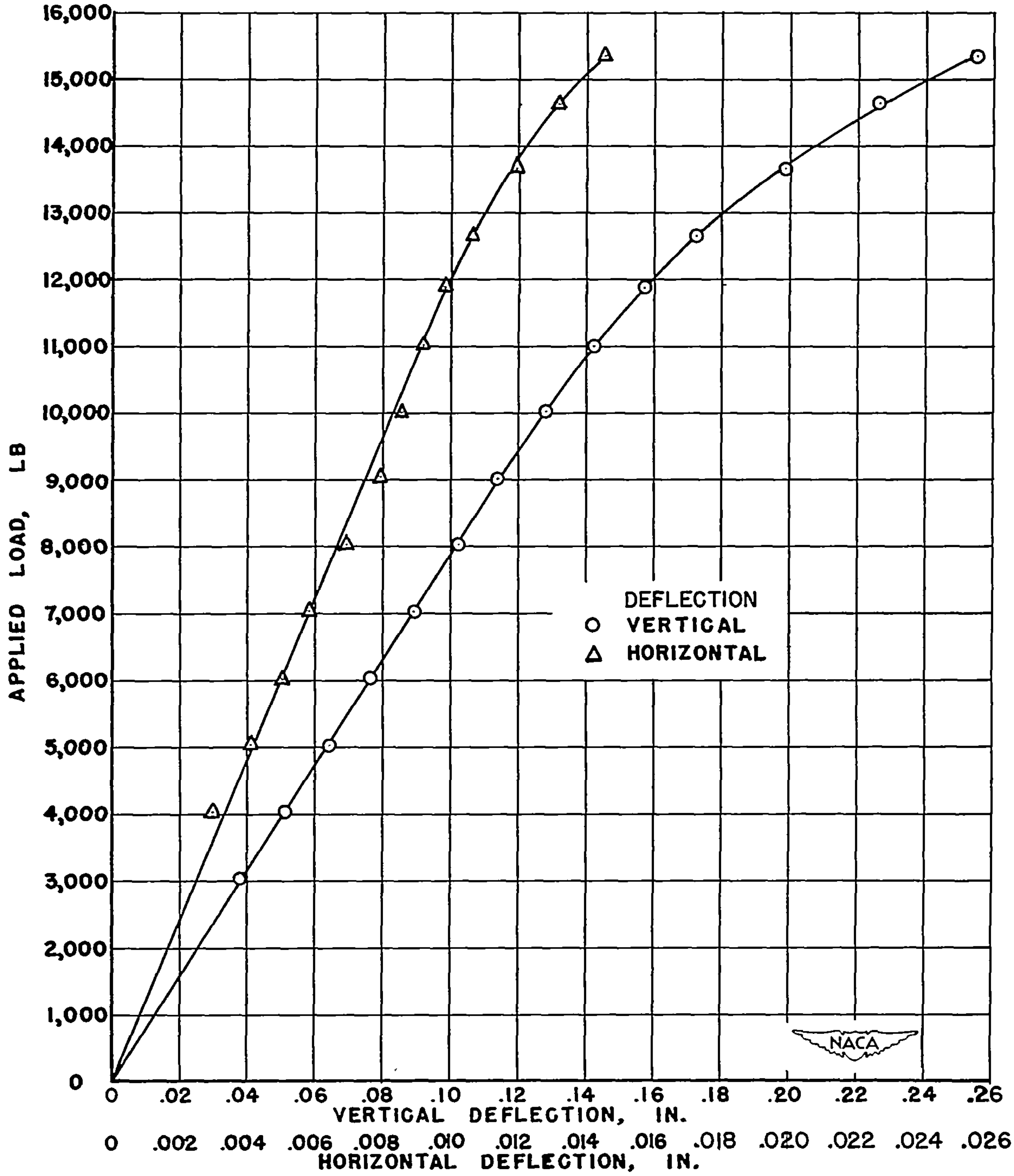

Figure 13.- Curves of deflection against applied load for truss I.

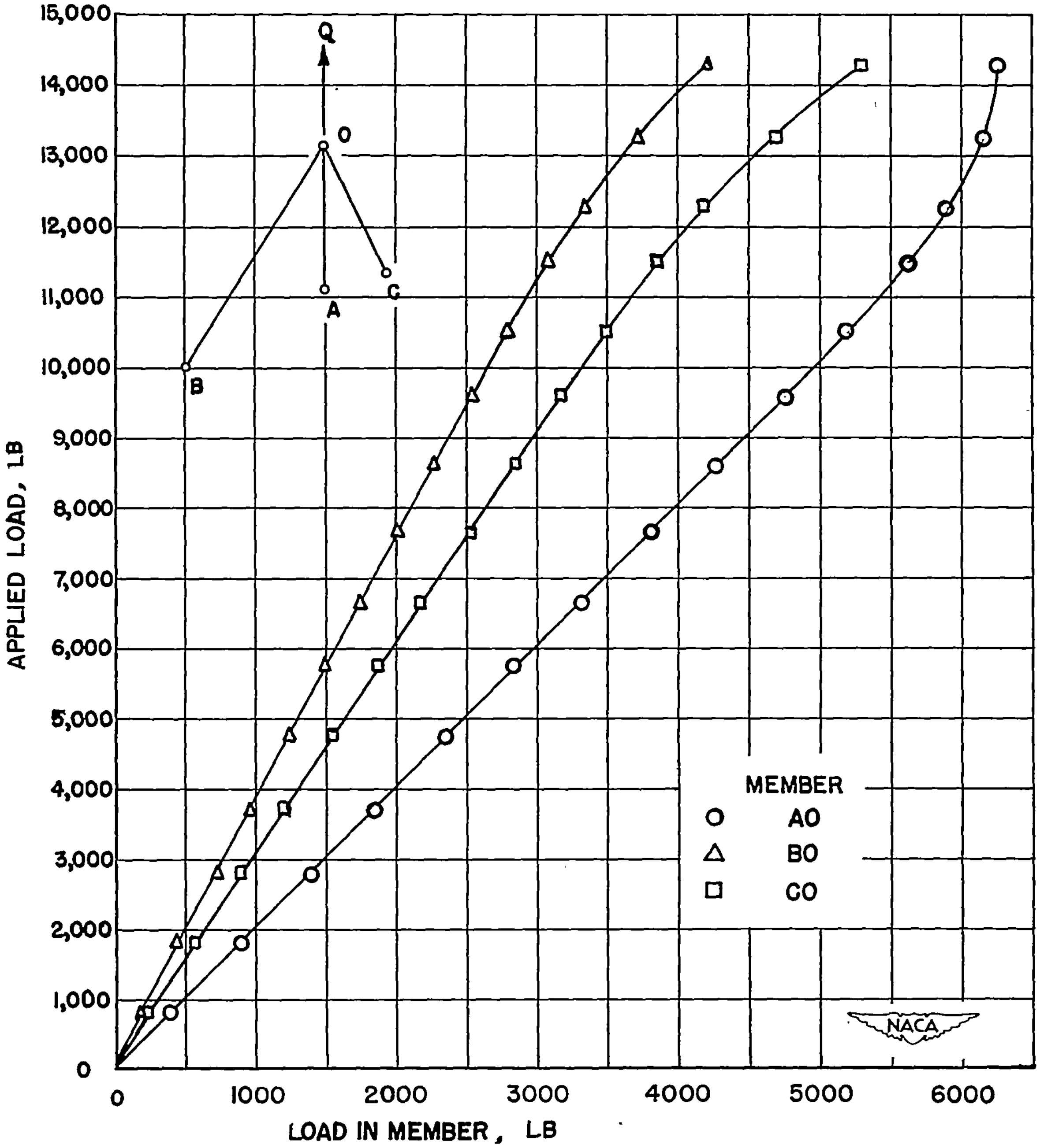

Figure 14.- Curves of applied load against load in members for truss II.

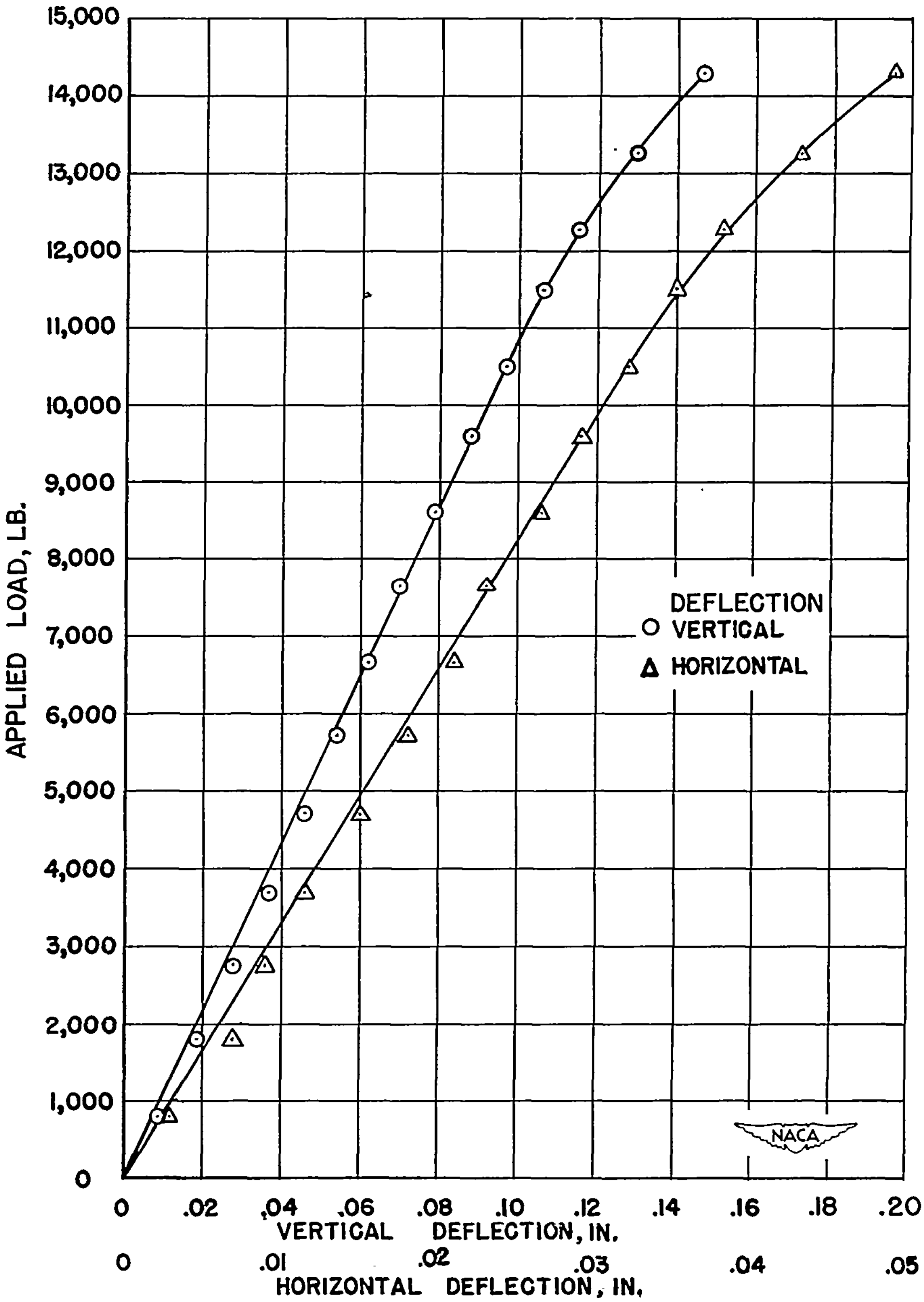

Figure 15.- Curves of deflection against applied load for truss II.

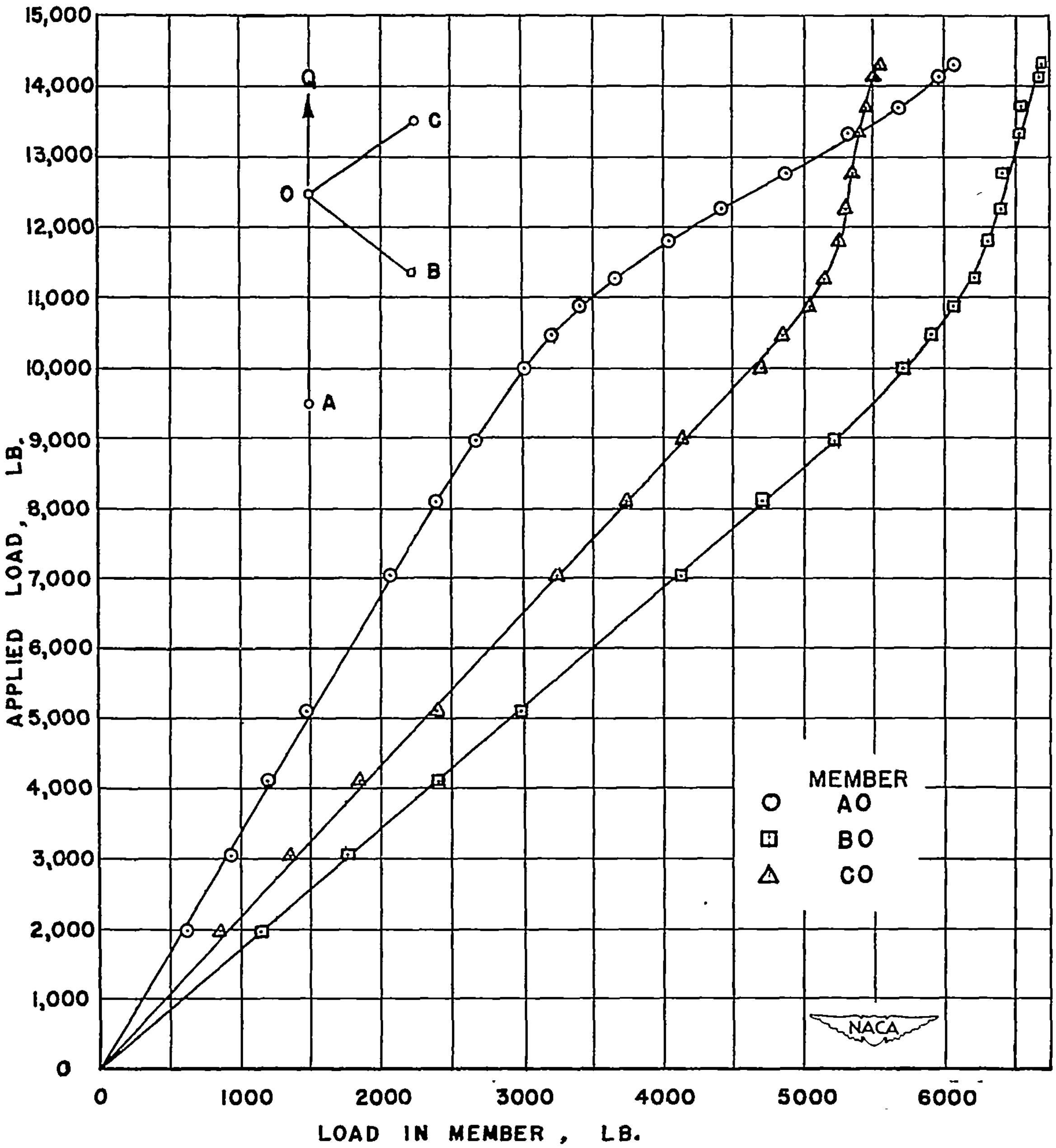

Figure 16.- Curves of applied load against load in members for truss III.

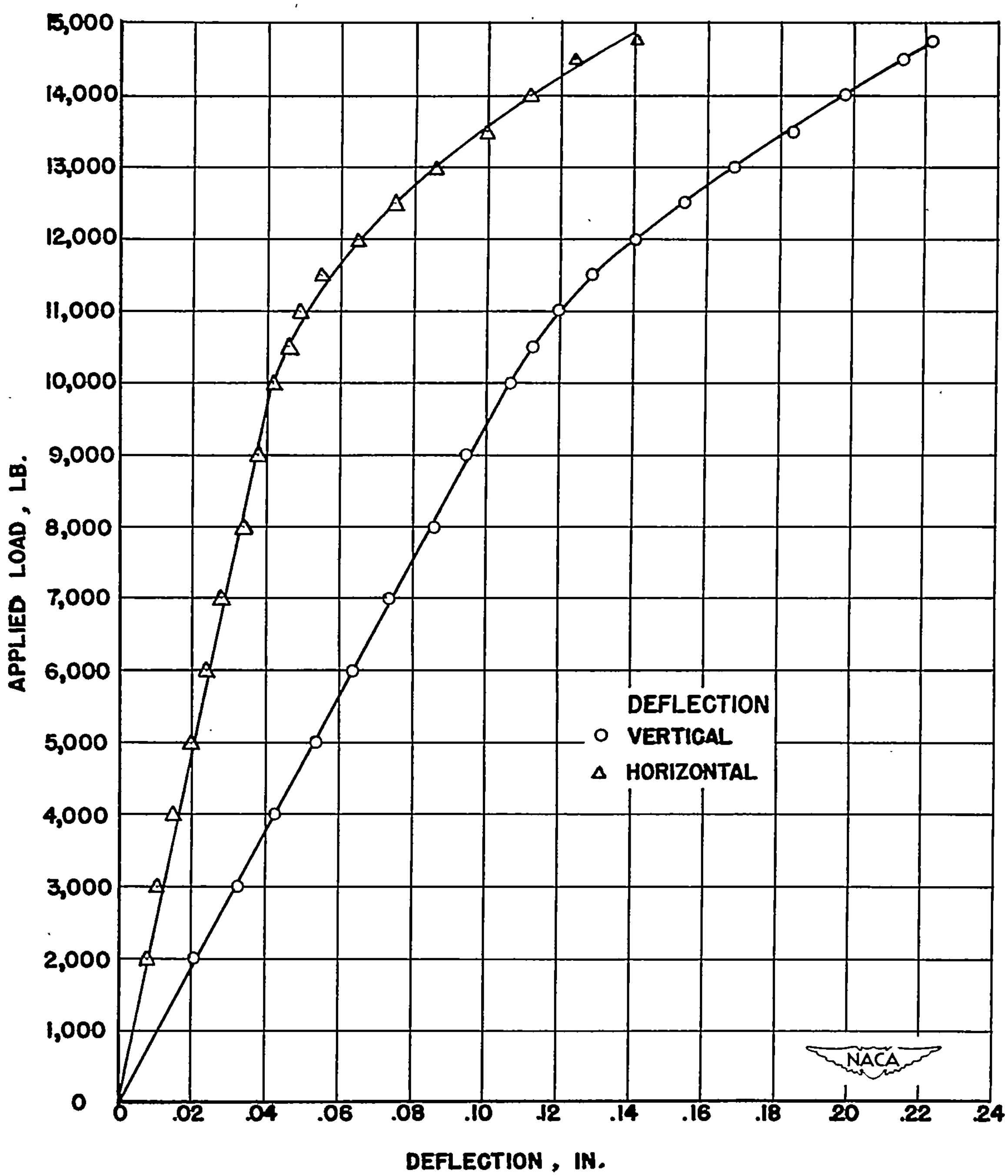

Figure 17.- Curves of deflection against applied load for truss III.

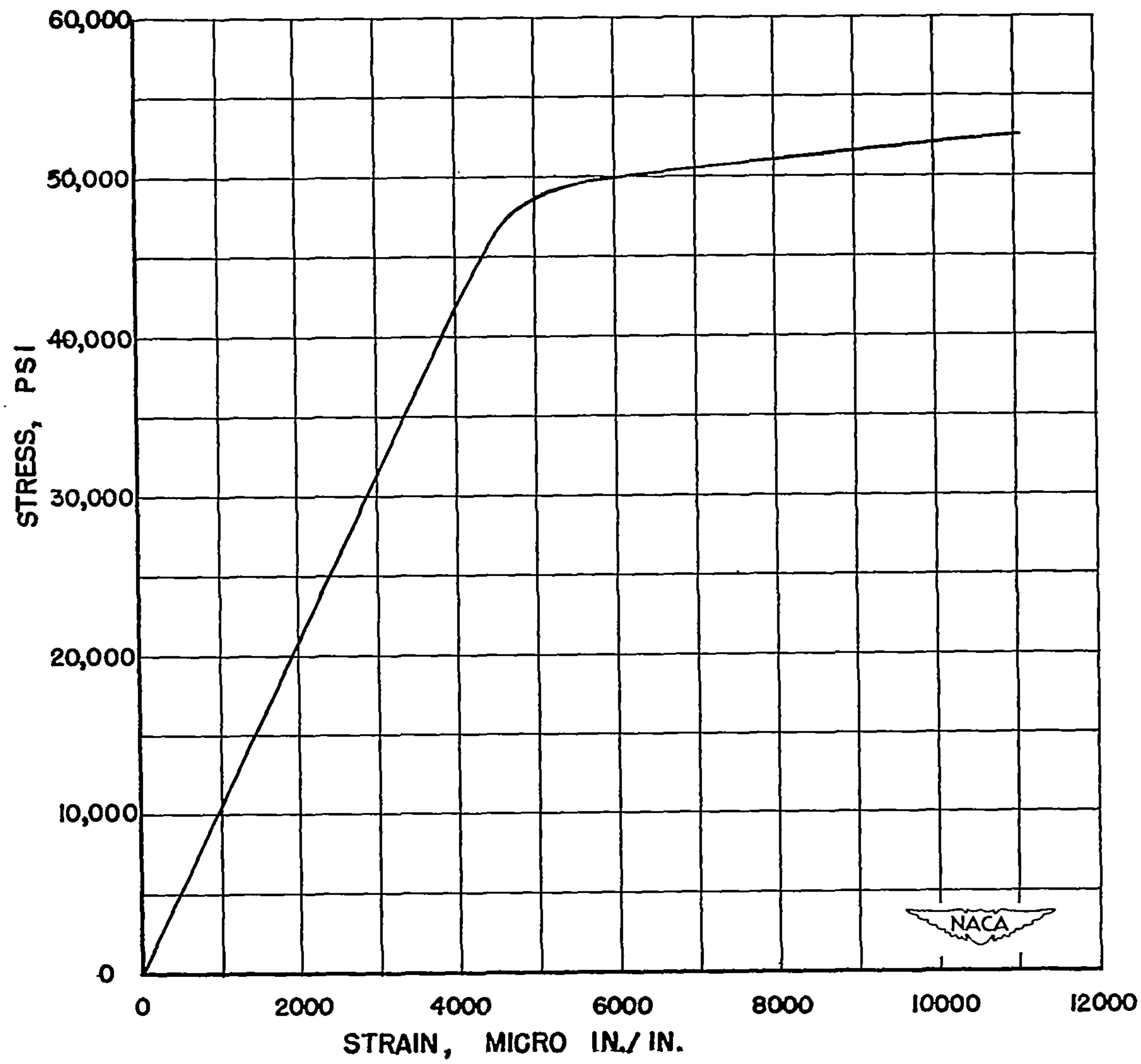

Figure 18.- Stress-strain curve for 24S-T4 aluminum alloy in tension. $E = 10.52 \times 10^6$ psi.

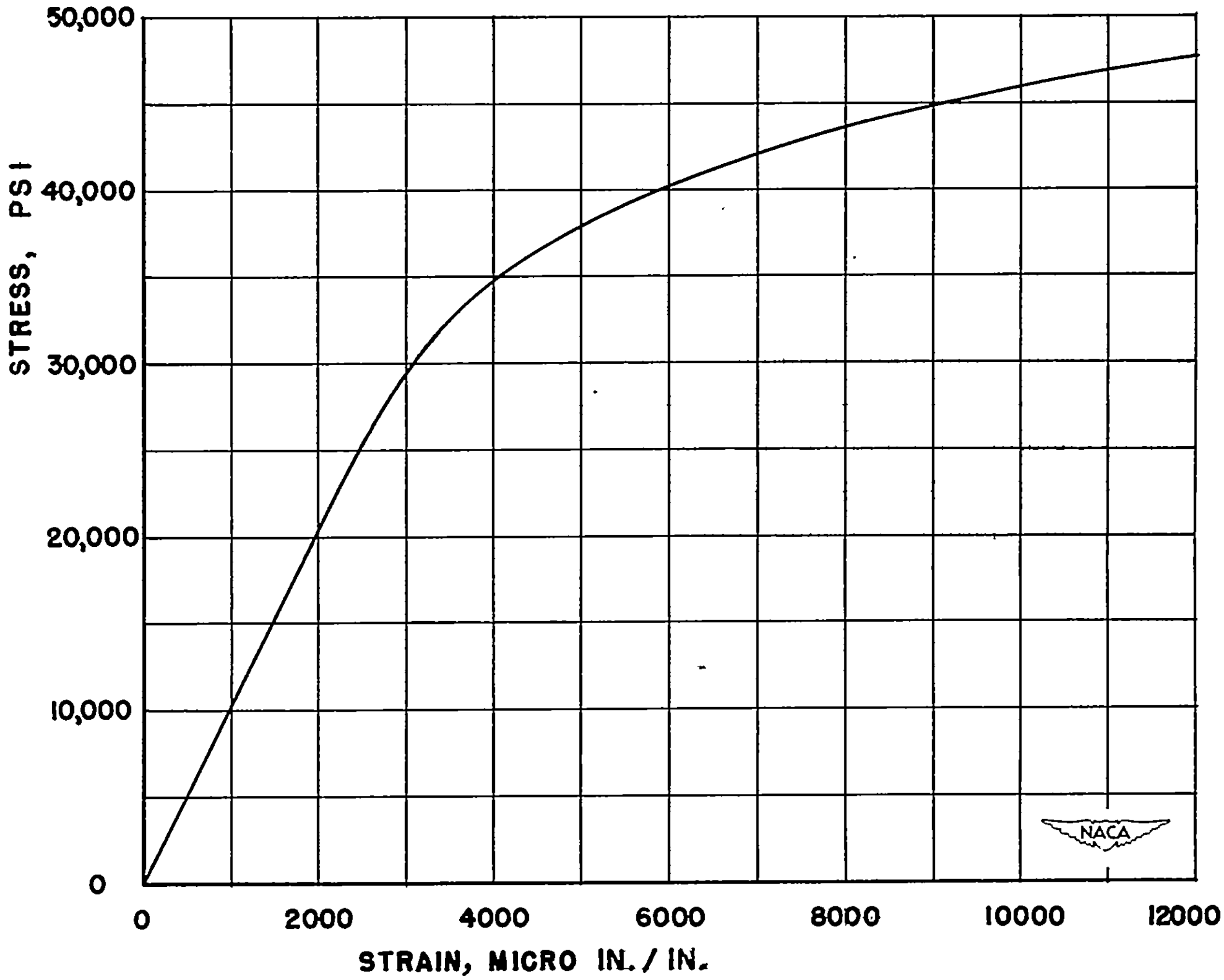

Figure 19.- Stress-strain curve for 24S-T4 aluminum alloy in compression. $E = 10.31 \times 10^6$ psi.

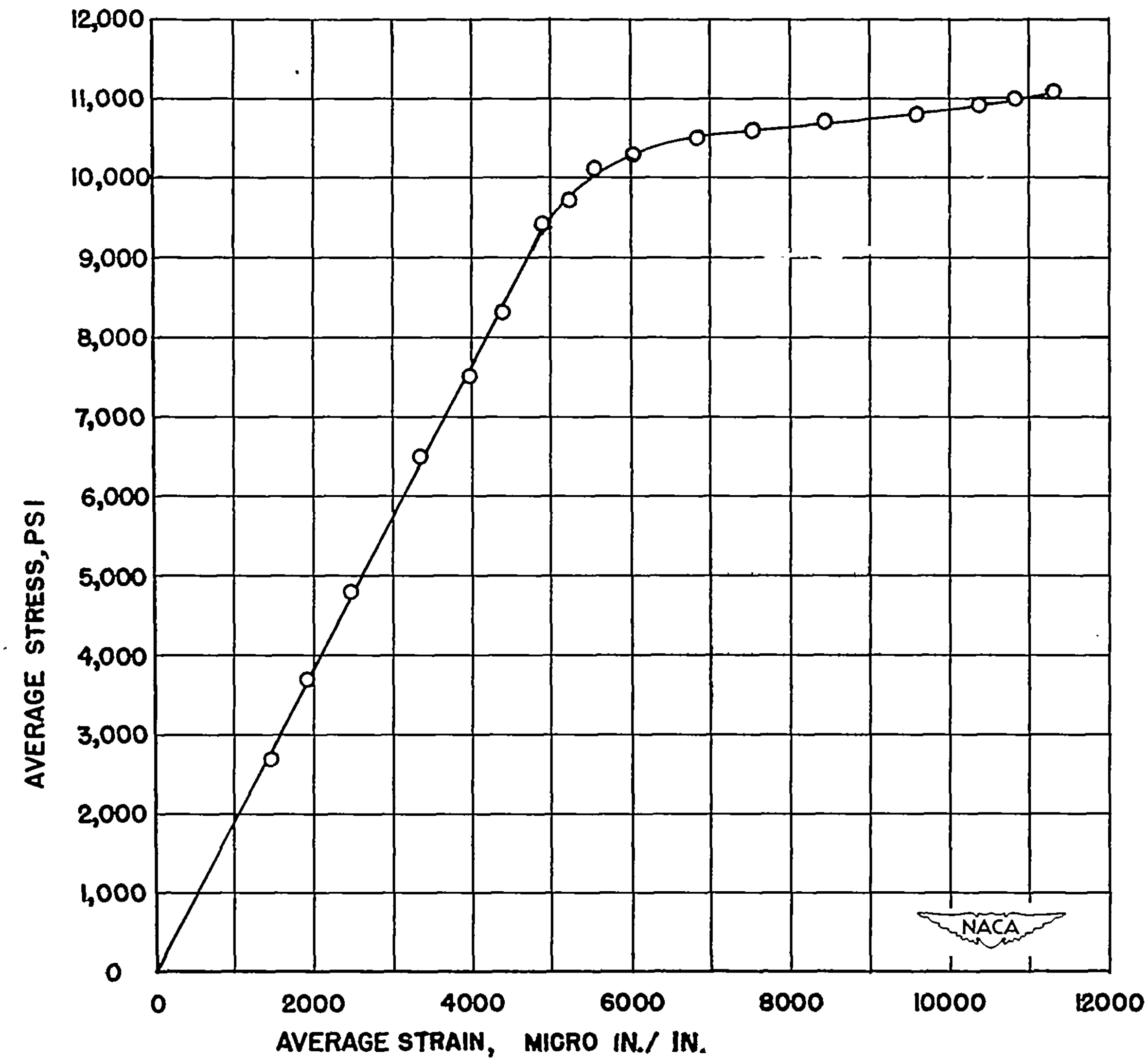

Figure 20. Average stress-strain curve for compression member in truss III.